Chapter 1. Introduction

1.1 History of Ultrasonic Flow Metering

As adolescents we all developed a fear of bats, associating them with unworldly monsters, while at the same time admiring their ability to navigate their nocturnal surroundings with little or no visibility. Perhaps one of the best examples of acoustic sensing in nature is echolocation; the process by which bats send out sound waves using their mouths or nose, and retain detailed information about their surroundings from the sound of the echo. In a similar fashion, acoustic waves can be used for flow diagnostics to collect information and data pertaining to the traversed medium. Ultrasonic flow metering, for example, given comparable fundamentals, is the process by which acoustic waves within the ultrasonic frequency range from 20 kHz to 2.45MHz are used to measure volumetric flow rates in pipelines.

Ultrasonic waves, or very high frequency acoustic waves, in liquids and solids have been used for many measurement applications including sonar, electrical filters, nondestructive testing, and medical instrumentation (Ristic, 1983). Two techniques, Doppler and transit time (Δt); have been used for flow measurement during the last century (Lynnworth, 1989). Early pioneers in the field include Herrick (1977), Chilowsky (1932) with his contributions for Doppler, and Rütten with his patents pertaining to transit time methods. Variations of the transit time of flight ultrasonic flow meter can also be traced back to the late R.C. Swengel, both a ham radio operator and inventor, who around 1947 or 1948 was able to obtain favorable results from his early
flow metering instrumentation in water. From the contributions of Swengel and others, ultrasonic flow metering technology has been developed over the past fifty plus years, and has evolved to support some of the most popular and efficient flow measurement devices available today. The non-invasive nature of ultrasonic flowmetering makes it highly applicable to oil and gas pipeline measurement systems, feedwater flow measurement, as well as a plethora of other areas where other types of flow meters are not appropriate due to their intrusiveness or associated pressure loss. Ultrasonic technologies have also been applied to oceanographic current sensors, interface sensors in beverage bottling plants, thickness monitors to control chemical depositions and etching, and arterial diagnostic systems to track blood flow throughout the body. As such, some of the more prominent benefits of ultrasonic systems include noninvasiveness, ease of operation and installation, fast response to flow variations, increased time between calibrations, and the modular design and interchangeability of components enabling rapid system repair. Not exclusive to the private sector, these ultrasonic devices can also be found in a domestic setting, utilized in hot water and methane metering systems used to monitor water and gas usage in large housing developments.

Ultrasonic transducers, the active elements in an ultrasonic flow meter, have two main functions: transmission and reception. Depending on the device and its purpose, there may be multiple transducers for each function, or a single transducer for all functions (Papadakis, 1999).
The most common of the ultrasonic flow meters in use today can be categorized into three categories; clamp-on, wetted, and hybrid. The utility of clamp-on meters is often the deciding factor in choosing an ultrasonic measurement system. Clamp-on flow meters, for example, can be installed without modifications to the metered channel or pipe, thus eliminating the need to empty or depressurize an area to allow for a sensor to be installed. For smaller diameter pipes, sensors can easily be positioned for measurement by an operator irregardless of skill level (Lynnworth, Mágori, 1999). Additionally, the often corrosive nature of internal sensors that remain in constant contact with the diagnosed fluid, adds considerable weight to an argument for using non-invasive instrumentation.

For example, to avoid water shortages and decreased water pressure, a removable transducer could be attached near the bottom of a water tower to monitor water levels. As the water supply diminished, the ultrasonic metering system might trigger pumps to replenish the supply back to acceptable levels. In this case, possible contamination of the
water supply by an invasive flow metering element may warrant the use of a clamp-on meter.

Although often effective solution, not all situations are conducive to the application of a clamp-on meter. In these cases the sensors or transducers utilized in the ultrasonic flow meter are of a *wetted* type, denoting there contact with the fluid. As such, *wetted* ultrasonic flow meters are integrated into the larger system much like conventional metering devices. For example, liquid presence detecting at a discrete point, based on detecting an echo from the far wall of a large liquid filled storage tank; sensing the change in ring-down when the probe is slid up and down the vessel wall to determine the fluid level; sensing change in ring-down at a fixed point when the level passes through that point; sending the sound wave vertically up through the liquid column and timing the round-trip (Lynnworth, Mágori, 1999). Figure 1.2 illustrates an example of a liquid level sensing arrangement using ultrasonic sound waves for a large fluid filled storage tank.

Combining the operational advantages of both the clamp-on and wetted types of transducers yields a *hybrid* type of meter. In this configuration, a wetted plug touches the fluid but the ultrasonic transducer is external, touching only the dry side of the plug, and removable at any time because physically only the plug is a permanent part of the pressure boundary (Lynnworth, Mágori, 1999). For example, a variation on the *wetted* configuration described above for liquid level sensing inside a storage tank could be converted to a *hybrid* type arrangement by placing the transducer outside of the vessel, with a reflector present inside the tank instead, thus isolating the transducer from direct contact with the fluid.
Given the abundance of operational, and process monitoring advantages to using an ultrasonic flowmeter as opposed to conventional mechanical metering techniques, one might inquire as to why the bulk of the flow meters in service were not of ultrasonic design. There are limiting factors which inhibit the use of these ultrasonic devices, many of which stem from the fluctuating dynamic conditions of the probed medium. Despite the advances in computing capabilities and subsequent improvements in measuring travel-time, ultrasonic flow meter accuracy has not improved very much at all. The explanation may be linked to the effect of turbulence on ultrasonic waves, primarily fluctuations in velocity and density (Andreeva, 2003). Andreeva examined, in detail, the
effects of a grid-generated turbulence on ultrasonic measurements, while restructuring the basic ultrasonic flow meter equation to account for the effects of turbulent velocity and sound speed fluctuations. The latter investigation was spawned from earlier experimental work by Weber (1994) that utilized the ray trace method to examine the effects of turbulent flows on sound waves propagation through a velocity field (Andreeva, 2003). Specifically, it was found in these studies that turbulence could result in substantial inaccuracy of volumetric flow measurements.

![Graph showing non-linear increase in acoustic travel time variance with increasing non-dimensional length scale X/M.](image)

**Figure 1-3 – Non-linear increase in the acoustic travel time variance with increasing non-dimensional length scale X/M.**

There are, of course, a large number of phenomena that effect transit time and, therefore, accuracy. The focus of this investigation will revolve around the effects of turbulence that contributes to a non-linear trend in the acoustic travel time variance. Figure 1-3 shows the theoretical predictions of Chernov (1960) and Iooss (2000) and
measurements made by Andreeva (2003). The acoustic travel time variance exhibits a linear increase for small values of $x/M$, where “$x$” is the ultrasonic path length, and “$M$” the grid mesh size. However, for large $x/M$ the acoustic travel time variance data increases and follows a non-linear trend, as illustrated in Fig. 1.3.

Second, the design of the acoustic travel time experiment is such that it allows us to examine the relationship between turbulent intensity and ultrasonic path lengths with regard to the acoustic travel time variance. As the ultrasonic path lengths increase and/or the characteristic grid mesh sizes decrease, the likelihood of a specific acoustic phenomenon called the caustics occurring, increased. Basically, ultrasonic waves actually converge on two-dimensional surfaces or planes in a three-dimensional volume called caustics, which can be described as a region on which two or more rays coalesce, producing high intensities. High acoustic intensities cause sound speed changes and spawning of upper and lower side bands so that the variability of the travel time increases.

These caustics thus, contribute to the scattering of the ultrasonic wave and overall variance of travel time with consequent error in the flow metering system. Considering that our analysis is based upon time of flight calculations, formulation of these acoustic disturbances is of paramount importance. In this work, we seek to verify, experimentally, that the higher the turbulent intensity, the shorter the distance at which the first caustics may occur.

Acoustic travel time data obtained experimentally which describes the non-linear trend in the acoustic travel time variance will be compared to preliminary findings by Durgin, Andreeva and Meleschi (Andreeva, et al. 2004) illustrated in Fig. 1.3. A
correlation between these preliminary findings and the data present herein, serves to validate our findings and support theoretical predictions of a non-linear increase in the acoustic travel time variance.

Given the background information presented pertaining to ultrasonic flow metering, a brief description of how sound propagates through random mediums is presented in the following.

1.2 Review of Sound Propagation through Random Media

Throughout the last half of the last century, technological advances in understanding how turbulence influences sound wave propagation have facilitated the continued development of improved ultrasonic devices for flow measurement. The scattering of sound waves in turbulent flows was first considered by Obukov in 1941; subsequently other authors have devoted papers to the same problem (Tatarski, 1961). Specifically, Tatarski (1961), as well as Ishimaru (1978) and Chernov (1960), include a wide variety of experimental and analytical data relating to wave propagation through the earth’s atmosphere and other relevant flows.

Atmospheric studies of electromagnetic and acoustic wave propagation were pertinent to radio physics, and attracted the attention of many investigators given their connection with the long distance propagation of V.H.F. and U.H.F. radio waves by scattering in the ionosphere and troposphere (Tatarskii, 1961). The turbulent state of the atmosphere promotes fluctuations in the refractive index of air. Sound propagation is sensitive to these random variations in the effective refractive index, which fluctuates as a
function of temperature and velocity. Di Iorio and Farmer showed that these medium velocity fluctuations can be a dominant source of acoustic scattering (Andreeva, 2003). Similarly, observations of sound wave propagation through temperature gradients confirm their impact on the refractive index and subsequent acoustic scattering. The index of refraction $n$ of the earth’s atmosphere, specifically in the troposphere (height $< 17$km), is given by (Ishimaru, 1978):

$$n - 1 = \frac{77.6}{T} (P + 4810 e/T) \times 10^{-6}$$  \hspace{1cm} (1.2.1)

whereas $T$ denotes the absolute temperature expressed in degrees Kelvin, $P$ the pressure in millibars, and $e$ the water vapor pressure in millibars. Thus, the problem of wave propagation and turbulence is one of the important problems in the areas of radio physics, atmospheric optics and acoustics” (Tatarskii, 1960) at large. Moreover, these atmospheric studies are of particular interest to our investigation in that the naturally occurring turbulent flow characteristics are comparable to those artificially maintained in the wind tunnel.

Although a large emphasis was placed on conducting outdoor experiments for atmospheric observations and measurements, these studies inherently featured a large degree of uncertainty in characterizing the surrounding environment especially turbulence. Physical parameters which describe these mediums, namely velocity and temperature, were not obtained exclusively, making it difficult to assess their individual contributions to the resulting acoustic wave behavior. However, because the nature of these environments are not well controlled, studies conducted within the turbulent or thermal field produced by a grid or jet in the laboratory may be more appropriate in
modeling an open air environment to examine how sound is influenced by turbulence (Benon, Juvé, Comte-Bellot, 1990).

Numerical techniques for simulating acoustic wave propagation through a turbulent medium were introduced by Benon, Juvé, Comte-Bellot circa 1941 in their studies relating to phase variance and the travel-time variance of acoustic waves moving through a random inhomogeneous medium. In generating their turbulent field, grid generated flows 40 grid-mesh lengths downstream were considered quasi-isotropic and in spectral equilibrium. Likewise, their spectral forms are comparable; and their statistical properties should only differ by a length scale $L_0$, and a turbulence level described by:

$$u'_i = \sqrt{u_i^2}$$

(1.2.2)

corresponding to the fluctuating velocity component in the $x_1$ direction. In addition an adapted von Karman spectral model for incompressible, isotropic turbulence was used to generate the simulated fields.

The ray tracing method was employed to simulate the actual movement of the acoustic wave. An initial position and direction of propagation of the acoustic wave front was assumed, and a point reference established thereon was used to follow the wave’s trajectory through the velocity field. In these simulations the transit times of the acoustic waves were considered to be small compared to the time scales of the simulated velocity fluctuations. Consequently, a “frozen” field treatment was adopted, descriptive of the static condition of the velocity field as observed in the frame of reference of the propagating wave. Effective application of the ray tracing method is presented at length in the papers of Andreeva (2003), and Webber (2004).
1.3 Review of Ultrasonics & Ultrasonic Flow Metering Methods

It’s is now over a decade since the Trans Alaska Pipeline (TAP) went into operation, an oil pipeline that runs 800 miles from wells at Prudhoe Bay to the port of Valdez. The pipeline’s flow sensor used in the leak detection system is an ultrasonic flow meter, developed by the Oceanic Division of Westinghouse Electric Corporation (Lynnworth, 1989). At present, the worldwide Ultrasonic Flow-metering market is expected to grow at a compound annual growth rate of 7.9% over the next 5 years. Evidence of ultrasonic technology’s value to industry as effective flow diagnostic solutions can be taken from Fig 1.4 which illustrates the Ultrasonic Flow Metering market size quoted in 2002 at nearly $406 Million dollars, is projected to expand to a $600 million dollar industry by 2007.

Transit time flow metering equipment is currently available from a relatively small number of vendors, with their applications primarily geared towards liquids over a wide range of operating temperatures. Ultrasonic flow diagnostic equipment was developed based upon the analysis of time of flight calculations for ultrasonic waves that traverse the mean flow of the probed medium. As these acoustic waves move through the probed medium, they inherently acquire information pertaining to their traveled paths. The exact instance that each ultrasonic wave is transmitted and then received is used to compute an acoustic travel time.
Information relating the traveling waves and the probed environment such as temperature, density, velocity, and traversed distances, etc. can be solved for explicitly using the relevant equations governing wave propagation. Typical accuracies for these instruments are on the order of 0.5%, with response times as short as 1 millisecond. Limits on performance and accuracy of ultrasonic travel time systems are imposed by factors that perturb the propagation of the transmitted signal. Specifically, anomalies such as gas bubbles or any other body that promotes scattering of the traveling waves, turbulence, acoustic interference, and signal jitter, etc.
1.4 Objectives and Methods

The primary goal of this thesis is to apply the travel time ultrasonic technique for data acquisition over the span of a grid-generated turbulence produced in the wind tunnel. Experimentally, we seek to observe the non-linear behavior of the acoustic travel time variance as it relates to changes in the turbulent intensity, velocity, and distance. Furthermore, the experimental design, consisting of two transducers positioned perpendicular to each other ($\beta = 0$), is such that the statistics of the collected data should confirm:

1. A non-linear increase the acoustic travel time variance predicted by Iooss (2000) at some propagation distance related to the occurrence of the caustics.

2. Theoretical and numerical investigations which predict that the greater the turbulent intensity, the shorter the distance needed to observe wave interaction and formation of caustics (i.e. non-linear trends in the travel time variance will appear at shorter propagation distances).

The body of this thesis is organized as follows. In Chapter 2 we review the defining flow characteristics of isotropic and grid-generated turbulence. In Chapter 3 we present the fundamental equations regarding wave propagation through random media, and highlight relevant works in the study of acoustic wave behavior. In Chapter 4 we present a description of our experimental apparatus and supporting data.
acquisition systems. The collected and analyzed data is presented in Chapter 5, along with a discussion of our experimental findings and comparisons to similar studies. Conclusions and our aspirations for future research are outlined in Chapter 6.